INTEGRATED OPTICS POLARIZATIION BEAM SPLITTER
USING FORM BIREFRINGENCE

BACKGROUND OF THE INVENTION

(1) *Field of the Invention*:

This invention relates to a method of spatially separating the two orthogonal polarization states of an incident optical signal. Its primary use is in integrated optics, where it is often desirable to split and manipulate an optical signal's orthogonal polarizations independently (polarization diversity). It can also be used in polarization mode dispersion (PMD) compensating devices, where the two orthogonal polarizations must be split, processed then recombined.

(2) *Brief Description of Related Art*:

Light is a vector field that has two primary and orthogonal polarization states or vector directions. These are sometimes referred to as the S and P polarizations in free space optics, or the TE (Transverse Electric) and TM (Transverse Magnetic) modes of optical waveguides. The performance of optical waveguides and optical devices is often sensitive to the polarization state. That is, the response of the device changes as the polarization state changes. This is particularly pronounced in integrated optical waveguides that are fabricated on dielectric substrates.

Typically, it is desirable to have optical components that are insensitive to the input state of polarization. This criteria arises from the fact that in fiber optic telecommunications, the polarization state of an optical signal that has traveled down any length of fiber is unknown, random, and time varying (due to perturbations in the environment). Great care is often taken in the design and fabrication of optical components so that they behave in a polarization insensitive manner. Despite this effort, most devices remain polarization sensitive to some degree, and this affects ultimate performance, yield, and cost. On the other hand, there are some special applications where the two polarization states of an input optical signal needs to be spatially split so each can be manipulated independently. This is the case for example, in PMD (Polarization Mode Dispersion) compensators, where the dispersion of the signal on the two states needs to be equalized. In applications where the polarizations need to be split, the extinction ratio, which is the ratio of wanted to unwanted polarization in either of the two branches, must be high.

Another general way to handle polarization in a device that is required to behave as if it were polarization insensitive is to split the input polarization into two branches having orthogonal states, process each branch independently with devices that are optimized for each polarization

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respectively, and then recombine the processed signals together. This scheme is referred to as "polarization diversity". It has the advantage that each branch can be specifically optimized for its respective polarization, giving the best performance without having to comprise the ability to give adequate performance over two polarization states simultaneously. The drawbacks are that twice the number of devices are required, and two polarization splitters are needed to split then recombine the signals. Naturally this adds cost and complexity, but the objective is to net an overall superior performing or higher yielding component.

Traditionally, optical components have been quite large, and polarization diversity schemes have not been popular because of the added size and cost associated with packaging twice the componentry plus the splitters. Prospects for polarization diversity improve for integrated optics fabricated on substrates, where the objective is to shrink the size of components and to integrate various functionalities on a common die or chip, similar in concept to integrated electronic circuits (ICs). In this case the polarization splitters and two sets of components are fabricated all at once. Future integrated optical components are miniaturized by the use of high-index contrast waveguides. High-index waveguides themselves are more susceptible to polarization sensitivity. Polarization diversity may be the only path forward for these future high-index contrast components.

Prior Art:

Most polarization beam splitters are bulk optic, and make use of birefringent wave plates. We will not discuss bulk optic polarization splitters here, but only emphasize integrated optic versions.

U.S.Patent 5,946,434 discusses an integrated optic Y-coupler polarization splitter. The splitter works by taking advantage of the difference in waveguide-to-waveguide coupling strengths for two orthogonal polarizations. The optimum structure is a result of an optimized coupling length. Both the coupling length, and the propagation constants are wavelength dependent, and therefore the polarization splitter will have a wavelength dependence, which is undesirable.

U.S. Patent 5,475,771 discusses an integrated optic Y-branching waveguide where one of the branches contains an anisotropic material. The structure requires the integration of an anisotropic material on to the integrated substrate. Such integration is not desirable because the two materials are not well matched in index (leading to scattering loss). Also the fabrication introduces additional steps that impact performance, cost, and yield. Most anisotropic materials can not be deposited by methods used to form the dielectric waveguides.

U.S. Patent 5,293,436 discusses an integrated optic Mach-Zehnder interferometer wherein one branch contains a polable material. Polable materials do not have long term stability, and are not used widely in telecom grade components. The polled materials tend to relax with a certain time constant (that is also affected by environmental conditions), and the performance degrades over time. Further, only certain materials are polable, and very few such materials make good passive low loss optical waveguides.

U.S. Patent 5,151,957 discusses an integrated optic delta-beta coupler configuration in X-cut Lithium Niobate. This method only works in Lithium Niobate, and is therefore not compatible with general integrate optic waveguides and materials.

U.S. Patent 5,133,029 discusses an integrate optic 2x2 beam splitter wherein the set of Y-junctions comprise waveguides of different widths. The waveguides forming the Y-junctions of this device must be comprised of anisotropic materials, and therefore limits the scope of this invention to those integrated optic waveguides using such materials (which is few).

U.S. Patent 5,111,517 discusses an integrated optic Mach-Zehnder in X-cut Lithium Niobate. This method only works in Lithium Niobate, and is therefore not compatible with general integrate optic waveguides and materials.

U.S. Patent 5,056,883 discusses an integrated optic Y-branching waveguide where in one branch contains a glassy polable polymer. This invention is similar to 5,475,771 above, where the anisotropic material is specifically an anisotropic polymer material (or a polable polymer material) that is deposited over only one branch of the Y-branching waveguide.

U.S. Patent 4,772,084 discusses an integrated optic 3x3 coupler. This invention is similar in its physical mechanism for polarization splitting as that described in 5,946,434 above, except that it uses a three-waveguide coupler instead of a two-waveguide coupler, and provides electrodes for post fabrication thermal or electro-optic trimming.

SUMMARY OF THE INVENTION

Figure 1 shows a schematic of an asymmetric four-port Mach-Zehnder interferometer comprised of two 3-dB couplers 11, 14 or power splitters and two branches 12,13 of lengths L_1 and L_2 as indicated. Consider the case where the structure is lossless, the waveguides in each branch are identical, and the TE and TM propagation constants of the waveguides are identical. Then the

responses at the two output ports are sinusoidal as a function of the branch length difference L_1-L_2, and are identical for both the TE and TM polarization states.

More generally, consider the asymmetric four-port Mach-Zehnder in Figure 1 wherein the waveguides in paths 1 and 2 are not identical, and the respective propagation constants of each of the waveguides are polarization sensitive. Then the responses are sinusoidal functions of the optical phase difference between the two paths for each polarization, given as

$$\Delta \phi^e = \frac{2\pi}{\lambda}(N_1^e L_1 - N_2^e L_2) \tag{1}$$

$$\Delta \phi^h = \frac{2\pi}{\lambda}(N_1^h L_1 - N_2^h L_2) \tag{2}$$

where $\Delta \phi^e$ and $\Delta \phi^h$ are the phase differences for the TE and TM modes respectively, N^e_1 and N^e_2 are the modal effective indexes of the TE mode in branch 1 and branch 2 respectively, N^h_1 and N^h_2 are the modal effective indexes of the TM mode in branch 1 and branch 2 respectively, and λ is the wavelength. In the lossless case, ports 1 and 2 are complementary. That is, the sum of the power at the two output ports is equal to the input power.

The objective of a polarization splitter in this invention is to have one polarization appear at port 1, and the orthogonal polarization to appear at port 2. It is also an objective to minimize the unwanted polarizations at each port. A figure of merit commonly used is the Extinction Ratio (E.R.). This is the ratio of wanted to unwanted power in each polarization for each port. In the Mach-Zehnder configuration, one output port for one polarization will have maximum transmission when the phase difference between paths is equal to

$$\Delta \phi^e = \pi + 2N\pi, \quad \text{where N is some integer} \tag{3}$$

The other output port, for the second polarization will have a maximum when the phase difference is equal to

$$\Delta \phi^h = 2M\pi, \quad \text{where M is some integer} \tag{4}$$

When the transmission is a maximum in one output port, it will be a minimum in the other output port. The design criteria for constructing a polarization splitter is to chose the path lengths L_1 and L_2, and the effective indexes N^h_1, N^e_1, N^h_2, and N^e_2 in such a way that equations (3) and (4) are simultaneously satisfied for some set of integers N and M.

In any polarization splitter design based on a Mach-Zehnder configuration, one must be able to design and fabricate waveguides that have substantially different propagation constants for the TE and TM modes. The term "birefringent" is used to describe the condition where the TE and TM modes of a single waveguide have different propagation constants. "Small" and "large" birefringence are terms used to describe conditions where the TE and TM modes are nearly identical, and far from identical, respectively. In the literature and in patent disclosures, birefringence is typically induced by poling a material having certain symmetries, such as Lithium Niobate, or by the anisotropic electro-optic effect in certain materials such as Lithium Niobate or Indium Phosphide. These types of birefringences are termed material birefringence because the material exhibits different indexes of refraction depending on the polarization state.

The invention described here makes use of form birefringence, also known as waveguide birefringence, and does not rely on material birefringence. Form birefringence is related to the waveguide geometry and structure, and can be induced in a number of ways, including the following.

1. *Changing the width of a waveguide.* (Fig.2) Changing the width of a waveguide with a lower chadding 21, a core 221, an upper chadding 23, and a cover 24 (while its thickness remains the same) changes both the average effective index, and the difference between the TE and TM effective indexes. In low index contrasts waveguides (where the core-to-cladding refractive index difference is less than about 0.02), the birefringence induced by changing the waveguide width is very small. However, as the index contrast increases, so does the change in birefringence. For index contrasts larger than 0.05, the induced birefringence is large enough to realize robust polarization splitters, as we demonstrate. Figure 2 shows a non-birefringent square waveguide 221, and a waveguide 222 having birefringence induced by narrowing the width.

2. *Creating non-homogeneous waveguides.* A homogeneous waveguide is one where the refractive index of the waveguide core is the same everywhere within the guiding core, and the refractive index of the cladding is the same everywhere within the vicinity of the core (practically, within 10 um of the core). Non-homogeneous means that the index within the core, or within the cladding, has a spatial variation. Layered or striated materials are also considered non-homogeneous. A non-birefringent waveguide can be made birefringent by

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placing a thin high-index layer 223 (higher index than the core) above or beneath the guide, as shown in Figure 3.

3. *Birefringent Material Overlay.* The method of 2 above can be generalized to a thin layer 224 of any index, but having a material birefringence. Example of overlays are stressy SiN, or polymers, as shown in Figure 4.

Form birefringence is a method to design the effective indexes N^h_1, N^e_1, N^h_2, and N^e_2 independently. This design freedom, in addition to the ability to specify L_1 and L_2, means that equations (3) and (4) can be satisfied simultaneously, and therefore, polarization splitters can be realized.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig.1 shows a schematic of an asymmetric four-port Mach-Zehnder interferometer..

Fig.2 shows the cross-section of a birefrigent waveguide with narrower core.

Fig. 3 shows the cross-section of a birefrigent waveguide with then high index layer.

Fig.4 shows the cross-section of a biregrigent waveguide with a thin borefrigent layer.

Fig. 5 shows the design of a form-birefrigent waveguide.

Fig.6 shows the top-down view of the first embodiment of the waveguides for the polarization splitter of the present invention.

Fig.7 shows the top-down view of the second embodiment of the waveguides for the polarization splitter with a heated section.

Fig.8 shows the top-down view of the third embodiment of the waveguides for the polarization splitter using a Mach-Zehnder balanced coupler as 3-dB couplers.

Fig.9 shows data taken from a fabricated polarization-splitter shown in Fig.8.

Fig.10 shows the top-down view of a fourth embodiment of the waveguides for the polarization splitter.

DETAILED DESCRIPTION OF THE INVENTION

Consider the waveguide structure that is shown in cross section in Figure 5. The core material is silicon oxynitride (SiON) with a refractive index of $n_{co}=1.70$. The upper and lower claddings are silica (SiO_2) and thermal oxide (thermally grown SiO_2) respectively, both with an index of $n_{cl} = 1.45$. SiON and SiO_2 can be deposited by chemical vapor deposition (CVD), which is well known in

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the integrated optics and semiconductor fields. Silica can also be deposited by flame hydrolysis (FHD), or by sputtering. Other suitable core materials include silicon nitride (SiN), silicon (Si), and Tantalum oxide-silica (Ta$_2$O$_5$:SiO$_2$) that is sputter deposited. Preferably the core to cladding index contrast (n$_{co}$-n$_{cl}$) is larger than 0.05, and we call such contrasts "high-index contrast". The desired waveguide height h can vary between 0.5 um to 4.0 um for high index contrast guides operating at a wavelength near λ = 1.55 um. Here it is selected as h = 1.5 um. The height is typically chosen so that the waveguide is single moded at the wavelength of interest. The width w will be varied to give a certain amount of form birefringence.

Using rigorous numerical models (Apollo Photonics, Inc. OWMS Suite), it is found that the effective indexes for the TE mode (N^e) and the TM mode (N^h) at a wavelength of 1.55 um follow the relations below as a function of waveguide width w,

$$N^e = 1.64233 - 0.325\exp[-1.5456w] \tag{5}$$

$$N^h = 1.63563 - 0.325\exp[-1.5456w] + 0.0547\exp[-1.339w] \tag{6}$$

The birefringence, which is the difference between the TE and TM effective indexes is,

$$N^e - N^h = 0.0067 - 0.0547\exp[-1.339w] \tag{7}$$

For a waveguide width of w = 1.50 um (square waveguide), the birefringence approaches zero.

The waveguide structure described above is used in the Mach-Zehnder configuration depicted in Figure 6. The Mach-Zehnder consists of two directional coupler type 3-dB couplers 111, 112 and 141, 142. The nominal waveguide width in the couplers is 1.50 um. The coupler lengths are chosen from simulation to be 45 um, and the cores are separated by 0.7 um. All the waveguide bends have radii of 300 um. The nominal width of the waveguides is 1.5 um. The path lengths in the Mach-Zehnder branches are set equal here, L$_1$ = L$_2$ = L$_{mz}$. There is a section of waveguide 122 (labeled w$_2$) having a width of 0.8 um in one arm of the interferometer. In this section the waveguide is tapered from a width of 1.5 um to 0.8 um over a length of 8 um. By narrowing the waveguide to a width of 0.8 um, a certain amount of birefringence is induced according to equation (7). The length of the narrowed section is chosen to be the polarization beat length, L$_p$. The polarization beat length is the

length over which the TE and TM modes accumulate a phase difference of π. It is given by the relation,

$$L_p = \left| \frac{\lambda}{2(N^e - N^h)} \right| \tag{8}$$

From (7) L_p is calculated to be 64 um at λ =1 .55 um. As outlined earlier in equations (3) and (4), two conditions must be met to have a high extinction ratio. Relation (8) is one condition. In order to satisfy (3) and (4) simultaneously, one can vary the waveguide width W_2 simultaneously with varying L_p. Another method is to change the difference in path lengths between the upper and lower branches of the Mach-Zehnder (L_1 and L_2 from Figure 1). A third method is to change the index of one of the branches by use of the thermal optic effect. Figure 7 shows the forgoing polarization splitter with a resistive heater 132 placed over one of the arms. Current injected into the resistor will heat that arm and can be used as a tuning or trimming mechanism. The heater changes the effective indexes of both polarizations by nearly the same amount, and does not itself induce significant birefringence. The heater used in the demonstration consisted of 200 nm of platinum deposited by an evaporator.

A further improvement is shown in Figure 8, where the simple directional coupler type 3-dB couplers depicted in Figures 6 an 7 are replaced by Mach-Zehnder balanced coupler[1] 113,114 and 143,144. The balanced couplers are 3-dB couplers with improved fabrication latitude and are more wavelength-independent compared to conventional directional couplers.

Data taken from the fabricated device in Figure 8 is shown in Figure 9. The numeric labels correspond to the port labeling of Figure 8. The graph is a plot of extinction ratio as a function of thermal tuning power applied to the resistive heater. Extinction ratio is the ratio of the power in one polarization state compared to the other state. As seen, the extinction ratios can be tuned up to 25 dB. Thus the heater gives a post fabrication method to optimize the performance. These polarization splitters can be cascaded output-to-input to increase the extinction ratios.

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[1] B. E. Little et. al. "Design rules for maximally-flat wavelength-insensitive optical power dividers using Mach-Zehnder structures", Optics Lett. Vol. ,pp. 1998.

Figure 10 shows the top view of the invention. The structure is similar to that shown in Figure 6. Compared to Figure 6, in this case there is no narrow section of waveguide on the upper branch. Instead, there is a section 123 of waveguide on the upper branch that has a thin layer of additional material. The material can be a thin high index layer as described in conjunction with Figure 3, or a thin birefringent layer as described in conjunction with Figure 4. The length of waveguide having this material layer is L_p. This thin layer of high index or birefringent material can replace the narrow section of waveguide of width w_2 in Figures 7 and 8.

While the preferred embodiments have been described, it will be apparent to those skilled in the art that various modifications may be made to the embodiments without departing from the spirit of the present invention. Such modifications are all within the scope of this invention.